TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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THE USE OF LARGE VALVE OVERLAP IN SCAVENGING A SUPERCHARGED SPARK-IGNITION ENGINE USING FUEL INJECTION

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SUMMARY

This investigation was conducted to determine the effect of more complete scavenging on the full throttle power and the fuel consumption of a four-stroke-cycle engine. The N.A.C.A. single-cylinder universal test engine equipped with both a fuel-injection system and a carburetor was used. The engine was scavenged by using a large valve overlap and maintaining a pressure in the inlet manifold of 2 inches of mercury above atmospheric. The maximum valve overlap used was 112°. Tests were conducted for a range of compression ratios from 5.5 to 8.5. Except for variable speed tests, all tests were conducted at an engine speed of 1,500 r.p.m. The results of the tests show that the clearance volume of an engine can be scavenged by using a large valve overlap and about 2 to 5 inches of mercury pressure difference between the inlet and exhaust valve. With a fuel-injection system when the clearance volume was scavenged, a b.m.e.p. of over 185 pounds per square inch and a fuel consumption of 0.45 pound per brake horsepower per hour were obtained with a 6.5 compression ratio. An increase of approximately 10 pounds per square inch b.m.e.p. was obtained with a fuel-injection system over that with a carburetor.

INTRODUCTION

Scavenging is the process of removing the exhaust gases from an engine. In the conventional four-stroke-cycle engine all the exhaust gases except those in the clearance space are forced out of the cylinder by the piston on the exhaust stroke. Consequently, the engine can not induct a charge of greater volume than that of the displacement volume; whereas, if the clearance volume could also be scavenged, the engine could induct a fresh charge equal to the displacement plus the clearance volume. The ratio of the power with complete scavenging to that with normal scavenging should be equal to the ratio of the volumes of the fresh charge, or $r/(r-1)$, where r is the compression ratio.

During the tests recently conducted by the Committee (reference 1) to investigate the valve timing of a supercharged engine at altitude and an unsupercharged engine at sea level, a scavenging blower was connected to the exhaust side of the engine in order to simulate the reduced exhaust pressures at altitude. In addition to the information obtained on valve timing, these tests show that at a compression ratio of 5.35 with the exhaust pressure reduced to that corresponding to an altitude of 18,000 feet the b.m.e.p. is increased 14 per cent. For this condition approximately 50 per cent of the exhaust gases were removed from the clearance space. Connecting the scavenging blower to the engine exhaust is not a practicable method for scavenging the engine because the power required to operate the blower would be greater than the corresponding gain in engine power.

As the superchargers now in use on engines of high power output could also be used as scavenging blowers, the engine induction system would not be further complicated, and the supercharger would instead serve a twofold purpose. To scavenge the clearance volume the valve timing of the engine would have to be changed so that both the intake and the exhaust valves are open during the last part of the scavenging stroke and the first part of the intake stroke. With this valve overlap the dead gases are blown out of the cylinder when they occupy the minimum volume. For this condition a large amount of the burnt gases in the clearance volume can be removed with a minimum loss of incoming charge. The carburetor should be replaced with a fuel-injection system so that the time of injection of the fuel could be controlled. It would undoubtedly be impossible to scavenge appreciably and to boost an engine equipped with a conventional carburetor without carrying some of the fuel out through the exhaust.

The use of a fuel-injection system instead of a carburetor for engines operating on the Otto cycle has been extensively investigated by the Committee during the past year. Such a system is suited to the use of "safety fuels" having a high flash point as well as of gasoline.

Power output practically equal to that with gasoline has been obtained using a hydrogenated safety fuel, although the fuel consumption is somewhat greater. During these tests it was found that the best performance was obtained when the start of the fuel injection period was from 50° to 70° after top center on the suction stroke. With this injection timing it is reasonable to assume that the scavenging can be completed and the exhaust valve closed before any fuel is injected into the combustion chamber.

Tests on valve timing (reference 1) showed that the power of an engine can be increased by advancing the time of intake opening and that the power is not greatly affected by retarding the time of exhaust valve closing. Therefore it is reasonable to suppose that a large valve overlap can be used without sacrificing performance of the individual cylinders. The effect of a large number of cylinders operating with a large valve overlap or long intake and exhaust periods would have to be considered in the design of the induction and exhaust systems. Most of the present tests were made at an engine speed of 1,500 r.p.m. using a fuel-injection system and using as a fuel domestic aviation gasoline (73 isooctane number) plus 10 cubic centimeters of ethyl fluid per gallon. These tests covered a range of compression ratios of 5.5 to 8.5 and two inlet pressures - atmospheric and 2 inches of mercury boost. A few tests were also made at 5.5 compression ratio with engine speeds of 1,200 and 1,800 r.p.m. with other conditions the same as in the preceding tests. Tests with no ethyl fluid in the gasoline were made at 5.5 and 6.5 compression ratios, at atmospheric inlet pressure, and at a speed of 1,500 r.p.m. The tests with the carburetor were made at 5.5 compression ratio and a speed of 1,500 r.p.m. The tests with carburetor were conducted with normal valve timing and with a valve overlap of 112°, while the tests with fuel-injection system were conducted with a valve overlap of 112°. All tests were made at full open throttle.

DESCRIPTION AND METHOD

These tests were carried out with the N.A.C.A. universal test engine, which is completely described in reference 2. A cross section of the combustion chamber of this engine is shown in Figure 2. An electric dynamometer is used to absorb the engine power. The compression ratio, valve lift, and time of opening and closing the valves can all be varied independently. The carburetor which is usually used with this engine was left in place and its throttles were used to control the air supply for starting. A Roots type supercharger driven by an electric motor supplied the engine with air at greater than atmospheric pressure. Two tanks were placed in the air duct between the supercharger and the engine to damp pressure pulsations. Figure 1 shows the set-up.

A commercial fuel-injection pump was driven from the crankshaft through a 2:1 reduction gear, which also served as a timing mechanism. A spring-loaded automatic-injection valve (fig. 2) set to open at a pressure of 3,000 pounds per square inch was used in the top spark-plug hole. The other two holes were used for the spark plugs of the double ignition system. The nozzle of the injection valve had seven orifices located to give a spray in a plane parallel to the crankshaft. This injection valve and nozzle were selected after several types had been tried.

Before the tests herein reported were conducted, the valve lift was set at three-eighths inch and numerous runs were made to determine the best valve timing. The settings finally decided upon were as follows: inlet opens 60° before top center, inlet closes 27° after bottom center, exhaust opens 47° before bottom center, exhaust closes 52° after top center. The events occurring at the bottom of the stroke were probably not timed quite as well as was possible, for they were at the limit of their adjustment, but from the data presented in reference 1, it seems probable that they were not displaced far enough from their optimum positions to affect the engine power appreciably. The events at the top of the stroke were at approximately their best positions, but their timing was not critical within 5° or 10°.

The adjustable pump-drive gear was set to give injection of fuel at the time that gave maximum power, and the actual time in the cycle at which injection occurred was determined by means of a "Stroborama". Injection started at 70° after top center on the suction stroke; the duration of injection was from 70° to 80°, according to the fuel quantity.

The torque at the dynamometer was read directly from dial scales, and the fuel consumption and engine speed were determined from the readings of an electrically operated counter and stop watch, which were connected to the fuel scales and gave the time and the number of engine revolutions required to use a given weight of fuel. For all conditions for which the fuel consumption was desired a series of at least three runs was made with fuel ratios varying from slightly richer than necessary for maximum power to lean enough to cause a decided drop in power. The ignition timing was set for maximum power whenever a change was made in the compression ratio. The maximum cylinder pressures were measured with a modified Farnboro electric indicator. (Reference 3.)

A short series of tests was made using the carburetor instead of the fuel-injection system. The carburetor used was a Stromberg NA-L5 model to which a needle valve had been added to give ready control of the mixture strength. An automatic regulating valve maintained the gasoline feed at a constant pressure over that of the inlet air. The carburetor runs were made with the needle valve adjusted to give the maximum power at full throttle with the least fuel consumption. For each condition the optimum ignition timing was used except for the 8.5 compression ratio, which necessitated retarding the ignition to eliminate detonation.

RESULTS AND DISCUSSION

In this investigation the scavenging pressures for practically all tests with the fuel-injection system were limited to 2 inches of mercury because the injection pump did not have sufficient capacity to supply fuel for the combustion of more air. The scavenging pressure for tests with the carburetor was limited to 6 inches of mercury. Figure 3 shows the b.m.e.p. and the specific fuel consumption obtained with different degrees of boost with a fuel-injection system and with a carburetor when the engine is operated with a large valve overlap. Similar performance data are shown for this engine with a carburetor when operating with standard Liberty timing or no valve overlap. No correction has been made for the power required to drive the supercharger for any of the data presented. This correction, however, would be very small, probably not over 2 or 3 per cent of the total engine power at 2 inches of mercury boost. It is reasonable to assume that some improvement in scavenging must be obtained with no boost pressure, or there would not be so great a difference between the b.m.e.p. with no valve overlap and the b.m.e.p. with a valve overlap. For the condition using a large valve overlap the b.m.e.p. at first increases with boosting at a much greater rate than with no valve overlap. For pressure differences between the inlet and the exhaust of more than 4 or 5 inches of mercury, the point where the curve indicates that the engine is almost completely scavenged, the rate of increase should be the same with either valve timing, with the actual value for the scavenged engine higher by a constant amount depending on the compression ratio. The fuel-injection system gives approximately 10 pounds per square inch b.m.e.p. more than the carburetor. The specific fuel consumption for a carbureted engine with no valve overlap and for a fuel-injection engine with a valve overlap decreases with the boost pressure; whereas, the fuel consumption for a carbureted engine with a large valve overlap increases with the boost pressure. The fuel consumption for the latter condition increases when the boost pressure is increased because some of the mixture is wasted in the scavenging process.

The effect of a large valve overlap on the b.m.e.p. and the fuel consumption at various compression ratios with fuel injection is shown by the curves in Figure 4. These curves show that the scavenging of an engine results in a large increase in power and an appreciable improvement in fuel consumption. The actual quantity of fuel injected per cycle, however, is greater when the engine is scavenged and boosted because the weight of air inducted is greater. It will be noted that with a more completely scavenged and boosted engine excellent economy can be obtained with exceptionally high power output. For instance, at a compression ratio of 5.5 and 2 inches of mercury boost the b.m.e.p. is 178 pounds per square inch and the fuel consumption 0.51 pound per brake horsepower per hour, as compared with a b.m.e.p. of 145 pounds per square inch and a fuel consumption of 0.54 pound per brake horsepower per hour for a carbureted engine operating with no valve overlap. (Fig. 3.)

Figure 5 shows the results obtained at compression ratios of 5.5 and 6.5 with domestic aviation gasoline compared with those obtained with domestic aviation gasoline plus 10 cubic centimeters of ethyl fluid per gallon. At a compression ratio of 5.5 very little improvement is noted in fuel consumption or power; whereas, at a compression ratio of 6.5 the power and fuel consumption are considerably better with doped fuel. Although no tests were made to determine the amount that the pressure at the intake could be increased without detonation with domestic aviation gasoline, it is believed that at a compression ratio of 5.5 the boost pressure could be increased at least to 2 inches of mercury.

Although most of the tests were conducted with sufficient ethyl fluid to eliminate detonation, a few tests were made with no ethyl fluid in the gasoline. There was no audible difference in the tendency to detonate with an engine having a scavenged clearance volume as compared with one that is not scavenged.

The curves in Figure 6 show the effect on power and fuel consumption of operating at speeds of 1,200, 1,500, and 1,800 r.p.m. The best performance was obtained at a speed of 1,500 r.p.m. and the poorest performance at 1,200 r.p.m. This large difference in performance may be caused by the length of either the intake or exhaust pipe or both. Previous tests have shown that at 1,500 r.p.m. the inlet pipe used was more favorable to high output than was no inlet pipe, and it is entirely possible that the exhaust pipe exerted a similar effect.

The explosion pressures were 660, 810, 870, and 830 pounds per square inch for a scavenged engine with 2 inches of mercury boost at compression ratios of 5.5, 6.5, 7.5, and 8.5. The explosion pressures for the 8.5 compression ratio were low because it was necessary to retard the spark to prevent detonation.

The operation of the engine was normal except at idling speeds. It is believed the idling could be improved by reducing the volume between the throttle and the intake port. With the present volume when the throttle is closed the exhaust gases from the cylinder flow into the intake pipe. On the following stroke these dead gases are inducted into the combustion chamber. The varying amount of these dead gases present for each cycle causes the engine to idle poorly. With the fuel-injection system and no valve overlap the engine idled satisfactorily.

<u>Mechanical considerations</u>. - The valve timing that is best for a supercharged engine at sea level is not necessarily the best at altitude because at altitude the pres-

sure difference between the intake and the exhaust valve is greater. Furthermore, the importance of using a scavenging blower decreases as the altitude increases because there is less exhaust gas in the clearance volume; the exhaust pressure being less. At an altitude of 18,000 feet there is approximately 50 per cent by weight less exhaust gas in the clearance volume at the end of the scavenging stroke than there is at sea level; hence, the increase in power due to scavenging the engine should be only 50 per cent of what it is at sea level. Because the pressure difference between the intake and exhaust increases with an increase in altitude on a supercharged engine the amount of compressed air wasted would have to be considered in the timing of the engine operating at high altitude. This wasted air need not be considered for engines operating at moderately low altitudes.

For engines equipped with turbosuperchargers the improvement due to scavenging would be obtained at all altitudes up to the critical altitude provided that the pressure at the intake could be maintained a few inches of mercury higher than the pressure at the exhaust. To obtain the best results with a turbosupercharger it may be necessary also to use a geared supercharger with a small compression ratio to give the necessary pressure difference.

The cylinder overlap must be considered also so that one cylinder does not starve another cylinder. It is believed that this difficulty with a fuel injection could be overcome by connecting each cylinder through a short intake into a common reservoir. The reservoir should be sufficiently large so that pressure fluctuations would not appreciably affect the charge to each cylinder. Any ramming action obtained with long inlet pipes due to the kinetic energy of the air could be compensated for by slightly increasing the pressure in the reservoir.

The fuel-injection system is more complicated than the carburetor, but it has some important advantages. In most carbureted engines some of the cylinders receive a richer mixture than others. This unequal distribution means that all of the mixture must be enriched until the leanest mixture which any cylinder receives is not too lean. Because better distribution can be obtained with a fuel-injection system than with a carburetor, the fuel injection should be more economical and give better acceleration and smoother running.

CONCLUSIONS

The results of these tests indicate:

1. That the clearance volume of a conventional four-stroke-cycle engine can be scavenged by using a large valve overlap and a pressure difference of from 2 to 5 inches of mercury between the intake and the exhaust valve.

2. That this improvement in the scavenging results in a large increase in power and slight decrease in fuel consumption.

3. That an increase of approximately 10 pounds per square inch b.m.e.p. was obtained with a fuel-injection system over that of a carburetor.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., January 25, 1932.

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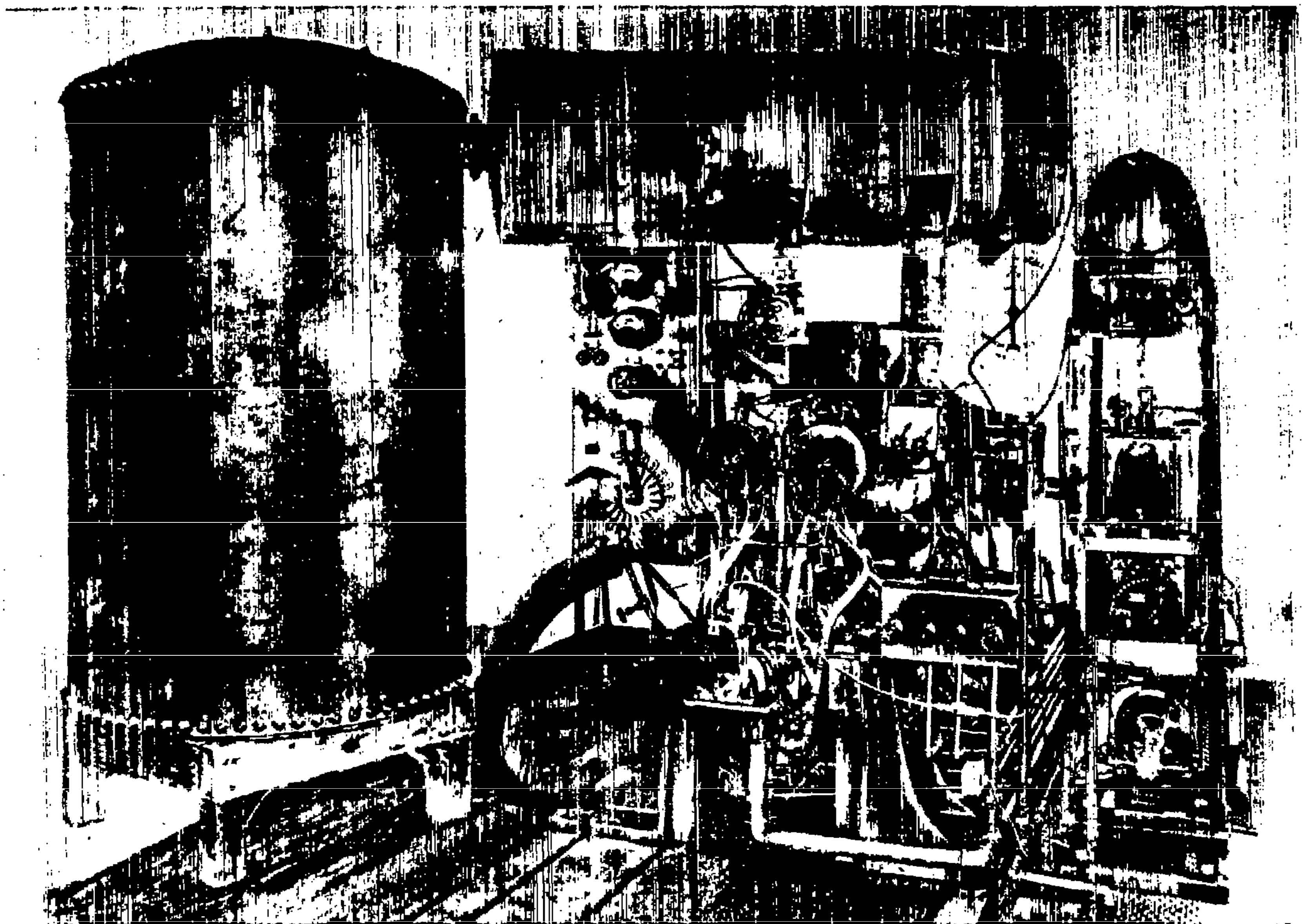


Fig. 1 Set-up of apparatus.

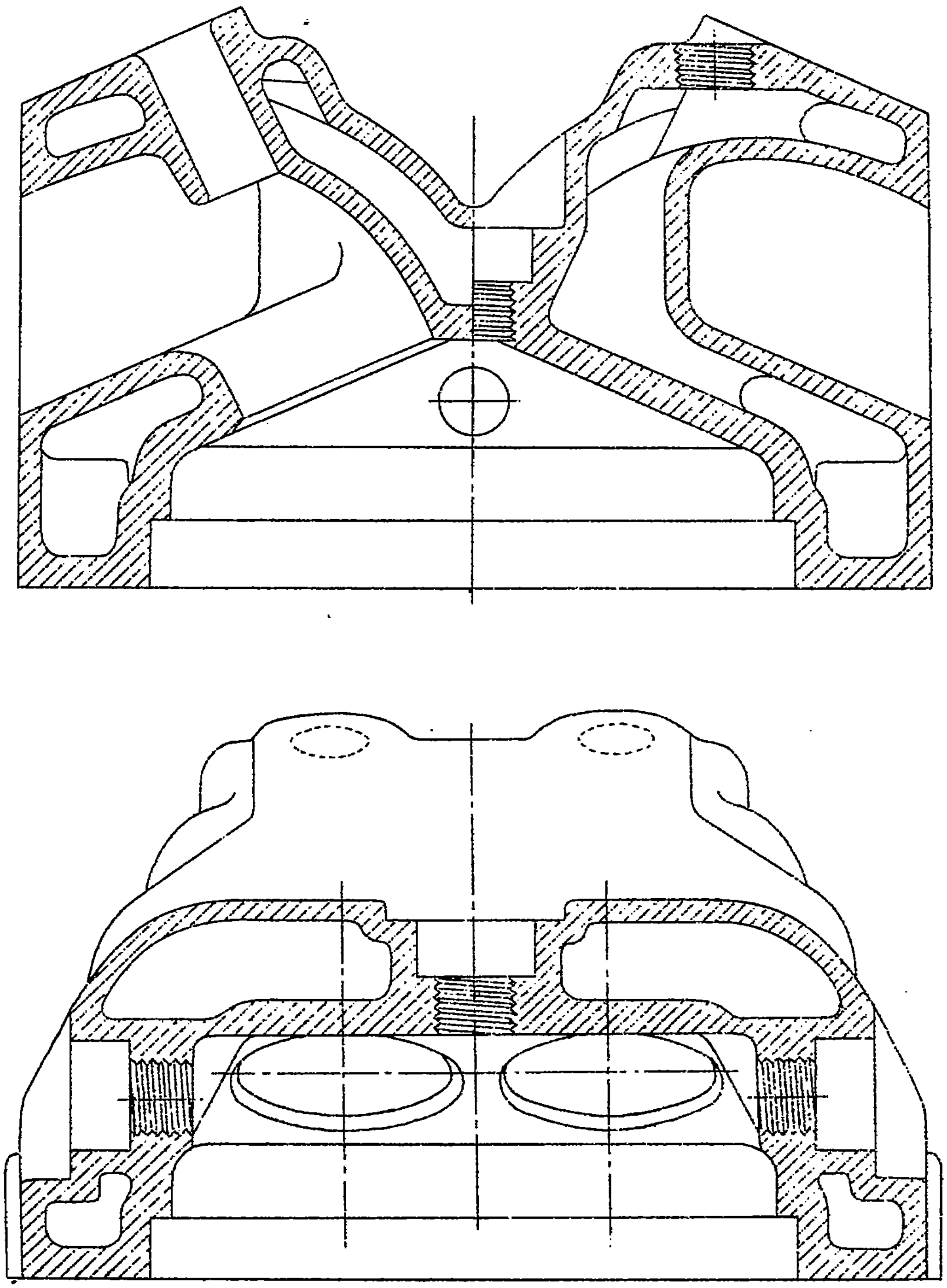
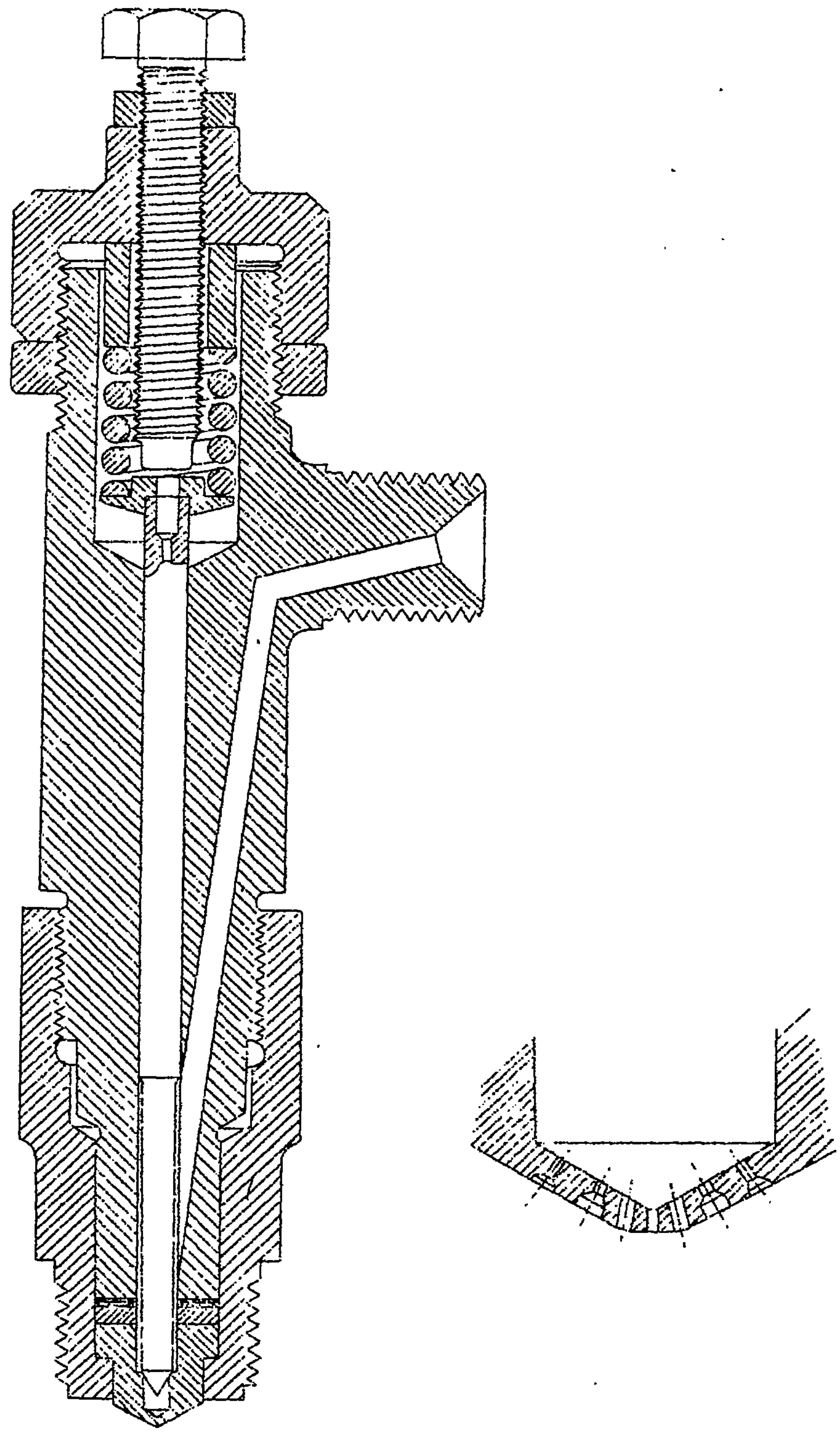


Fig. 2 (Continued on next page.)



Continuation of Fig.2 Combustion chamber and fuel-injection valve used.

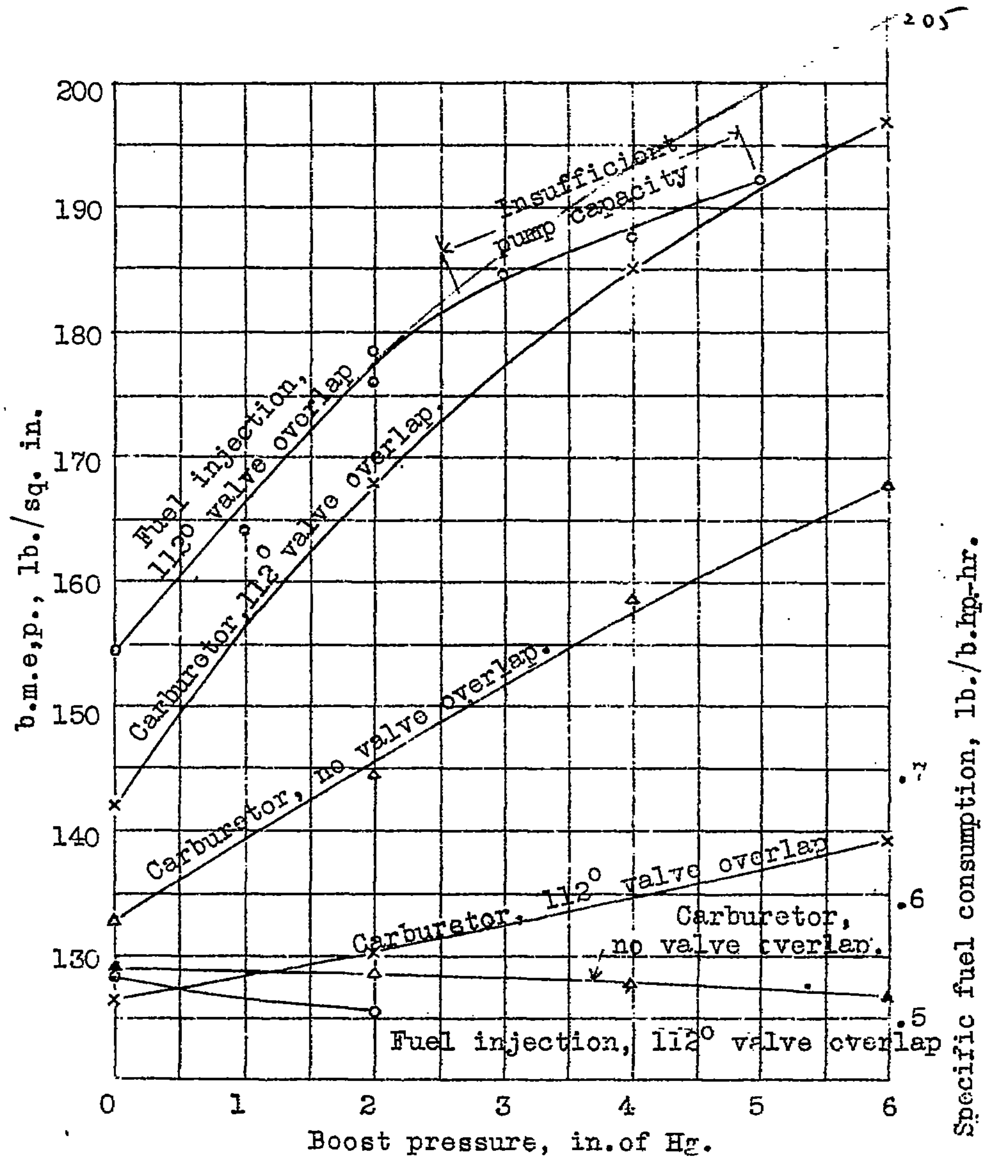


Fig. 3 Power and fuel consumption at 5.5 compression ratio with 112° valve overlap for both fuel injection and carburetor operation and without overlap using the carburetor.

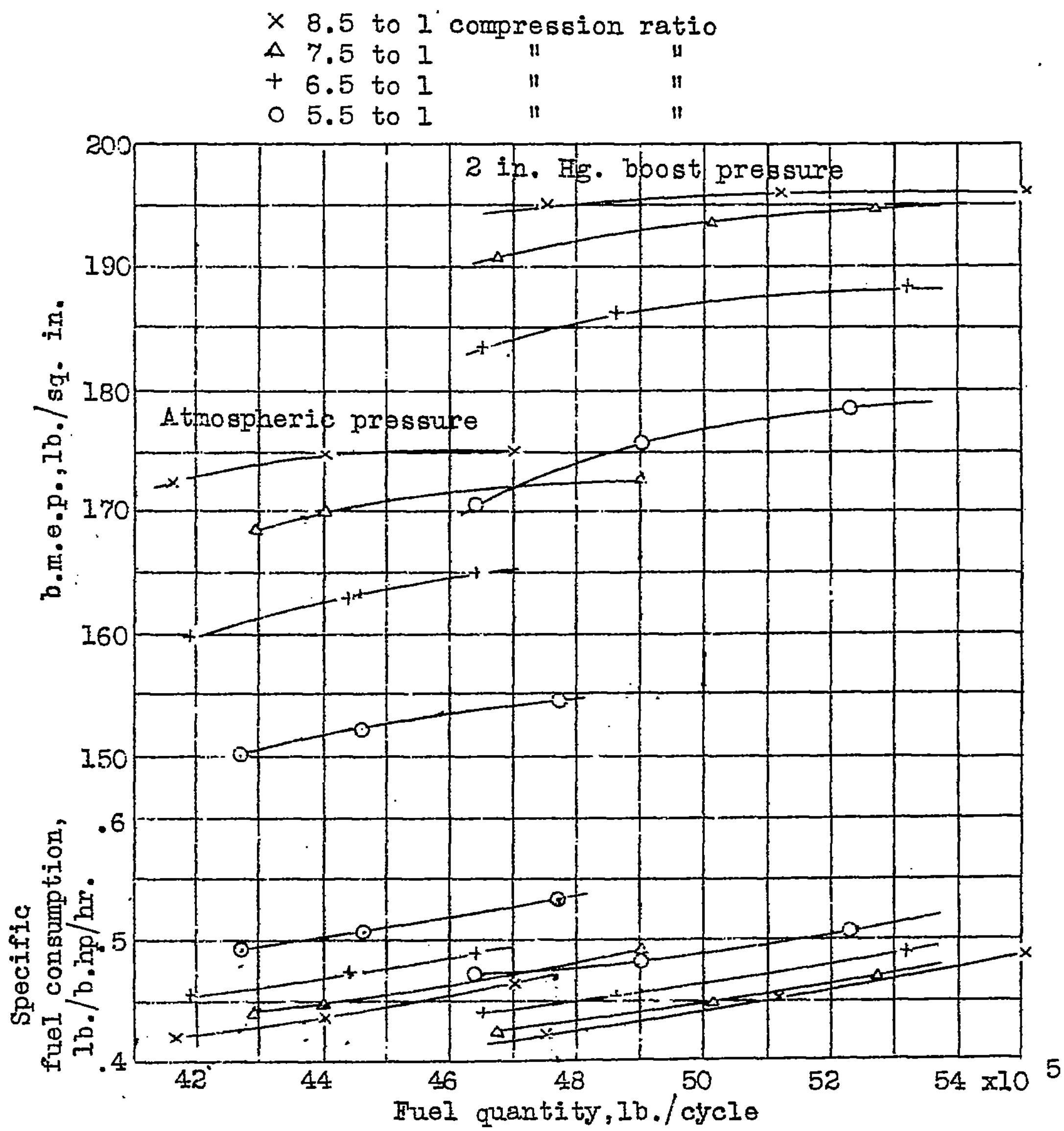


Fig.4 Power and fuel consumption with 112° valve overlap and fuel injection for different compression ratios and boost pressures.

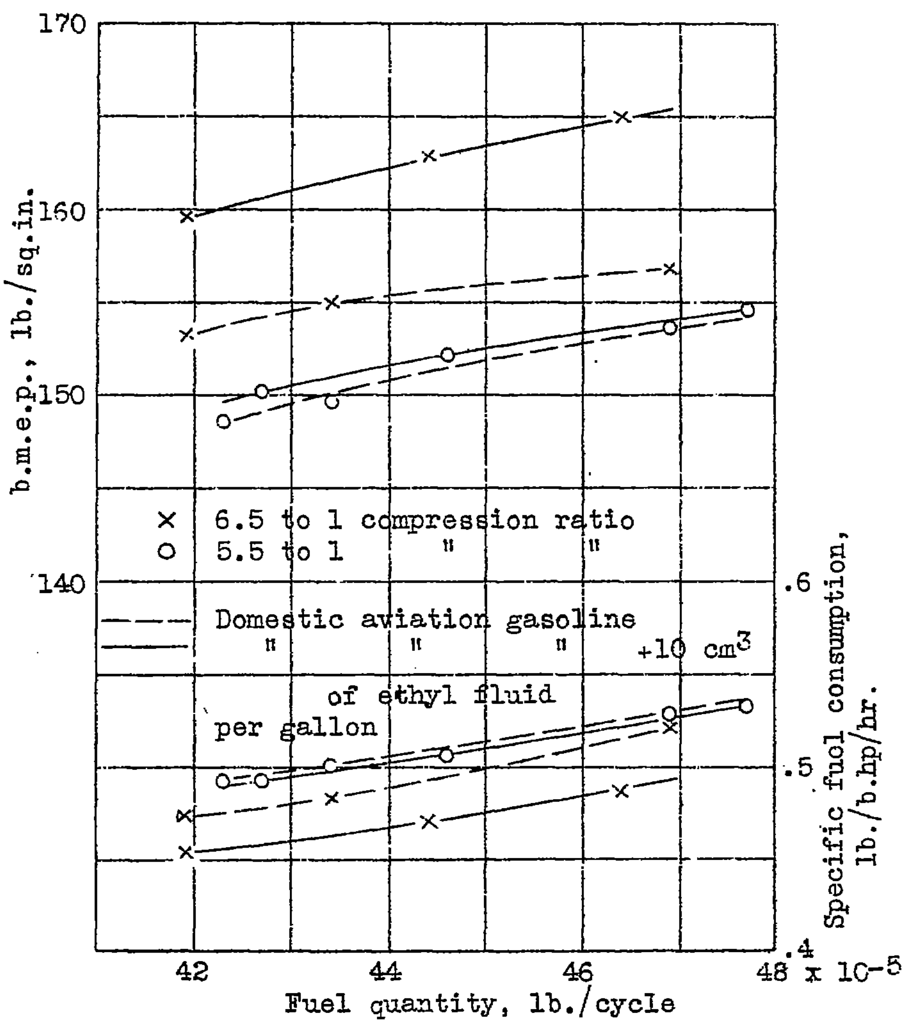


Fig. 5 The effect of the addition of 10 cubic centimeters of ethyl fluid per gallon to the fuel on the power and fuel comsumption when operating with 112° valve overlap and fuel injection.

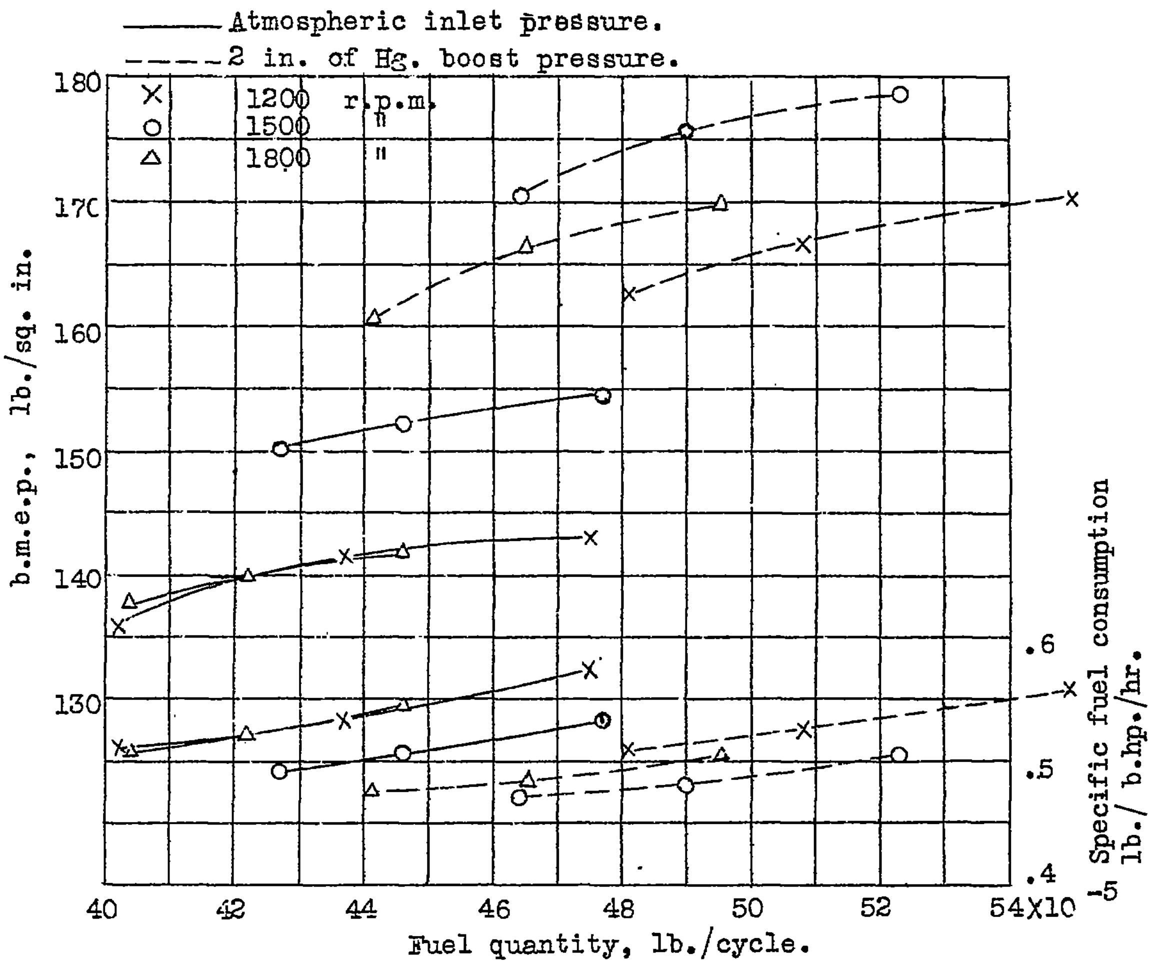


Fig. 6 Power and fuel consumption at different speeds and boost pressures for a compression ratio of 5.5 when operating with 112° valve overlap and fuel injection.